

Fermilab

p Note #399

Bunch Coalescing RF Cavities at $h = 53$

In Main Ring Operational Procedures

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The longitudinal emittance of p beam injected into the Main Ring is about 1.5 ev-sec. But Main Ring is not capable of accelerating such a large emittance in a single bunch without excessive particle loss at 8 GeV so that the beam is broken up to several (4-11) adjacent bunches accelerated to 150 GeV and reconstituted into a single bunch at 150 GeV. Two P.P.A Cavities are used for constituting.

The P.P.A Cavity is a double cavity and a drift tube inserted within it. 750 Kg of Ferroxcube 4C4 are used to resonate a double cavity over the frequency range 6 to 30 MHz. It is realized by tuning DC bias current. Two 4CW 10000 tubes work in push-pull to excite the cavity. The bus bars couple two halves cavity together. After it was being overcoupled during its operation the tuning bus bar will be removed. This means that tuning DC bias circuit has been broken and one cavity was

broken up to two. Fortunately the cavity will only be operating at one frequency. Fig 1 is P.P.A Cavity in longitudinal section.

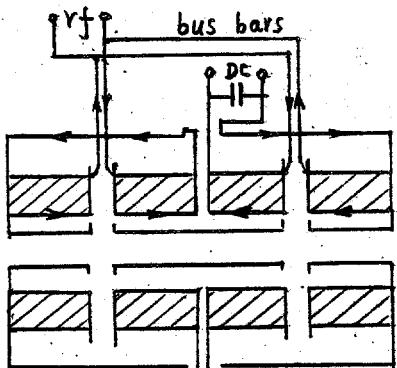


Fig 1 P.P.A Cavity in longitudinal section

In order to constitute 13 $h=1113$ bunches into a single bunch at 150 GeV. Using $h=21$ ($f=1\text{MHz}$) bucket to manipulate the beam was suggested, but p.p.a. can not work at such a low frequency because of magnetic field flux intensity B and power loss too high, so a $h=53$ with some higher harmonic terms added non-sinusoidal RF bucket is used. When $h=1113$ buckets are about 20s . Calculation shows the non-sinusoidal wave has to have about 1.24π linear portion in length. According to calculations the peak voltage needed is about 22kV . The waveform is shown in Fig 2 (a). The function of $f(\omega t)$ is as follows

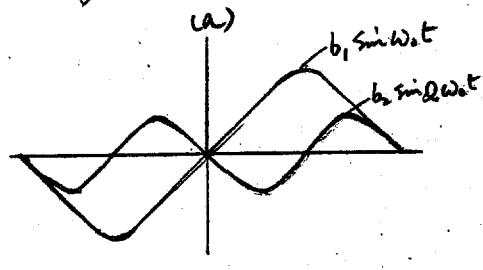
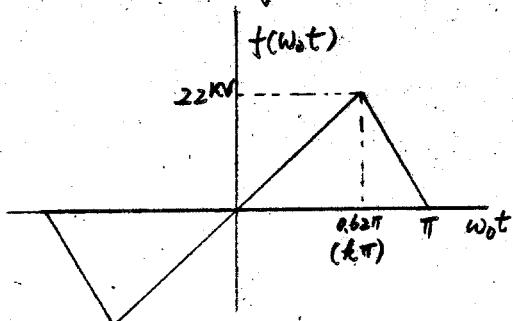


Fig 2. a) Requirement waveform

$$f(\omega t) = \begin{cases} \frac{1}{(1-k)\pi} \omega t & 0 \leq \omega t \leq (1-k)\pi \\ \frac{1}{k\pi} (\pi - \omega t) & (1-k)\pi \leq \omega t \leq (1+k)\pi \\ \frac{1}{(1+k)\pi} (\omega t - 2\pi) & (1+k)\pi \leq \omega t \leq 2\pi \end{cases}$$

Fourier Waveform analysis

$$f(\omega t) = \sum_{n=1}^{\infty} b_n \sin n\omega t$$

$$b_n = \frac{2}{\pi} \int_0^\pi f(\omega t) \sin n\omega t d\omega t = \frac{2 \sin((1-k)\pi)}{n^2 \pi^2 k (1-k)}$$

$$\text{If } k=0.62 \quad b_1=0.80 \quad b_2=0.147 \quad b_3=0.0407 \quad b_4=0.058$$

$$V_{\text{peak}}=22\text{kV} \quad V_1=17.6 \quad V_2=3.23 \quad V_3=0.89 \quad V_4=1.18$$

b) fundamental and second harmonic If $k=a$, $b_1=0.78$, $b_2=0.229$, $V_1=0.033$, $b_4=0.035$
components and relative phase $V_{\text{peak}}=22\text{kV}$, $V_1=17.17$, $V_2=5.04$, $V_3=0.704$, $V_4=0.77$

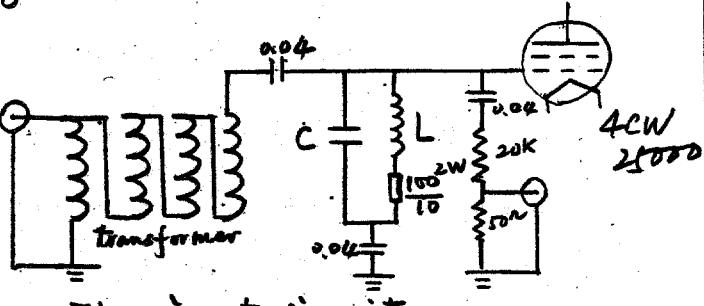
It is seen that the fundamental and second harmonic are important. all other higher harmonic terms only have a small influence. Fig 2(b) shows the phase relation of them.

In order to satisfy the requirement of longitudinal manipulating, the P.P.A cavity has to be rebuilt. The input circuit and output circuit have been modified.

The basic idea for input circuit is to make it as simple as possible and low driving power needed. Since cavity only operates at a single frequency and tuning D.C. bias circuit is not used, the one end of input circuit has been grounded, it makes driving and measurement easy.

The input resonant circuit simply consists of a air-cored Solenoid and a capacitor. A new transmission transformer has been used. The ratio of input voltage to output voltage is $\frac{1}{4}$, the ratio of impedance about $\frac{1}{16}$. Using this transformer the driving power can greatly reduce at the same input impedance and it gives a possibility using higher grid bias voltage to reduce conductive angle of tube consequently to enhance the efficiency. The driving peak voltage at grid never reached 600° , after transformer changed it can reach to about 1000° . As the driving power and Duty factor ($< 3\%$) are low, the input terminal load is not necessary. But for reducing Q and making input impedance 50Ω at resonant frequency, ten $2W$ 100Ω resistors paralleled are put into the resonant circuit. The Q is about 12.

The input circuit shows in Fig 3.



Sometime for only one cavity Working and higher output power needed in future 4.CW25000 tube has been used.

There are two methods to add higher harmonic terms. One is that three half cavities work at the fundamental frequency and one half cavity works at second harmonic, then four gap voltages superimposed. This is simple and easy but it will increase a number of hardware of driving and control. It is difficult to get requirement RF Voltage in only one cavity; because the half cavity (one gap) which is operating at fundamental frequency can not get such a high Voltage (about 17.5 KV peak). The other method is that both fundamental and second harmonic Voltage get in one gap (a half cavity). Even though this is difficult, the efficiency is high and it gives a chance the voltage needed gets in one cavity. The latter are described here.

As one knows a pulse of plate current delivered by the tube operating in class C to the output circuit contains components of the fundamental and most higher harmonic frequencies. To generate output power that is a harmonic of the exciting voltage applied to the control grid, it is merely necessary to resonate the plate circuit to the desired harmonic frequency. If the plate circuit consists of two series circuits which resonates at fundamental frequency and second harmonic frequency respectively, the plate output power will contain two frequency components. The

non-sinusoidal Voltage Waveform depends on amplitudes and relative phase between these components.

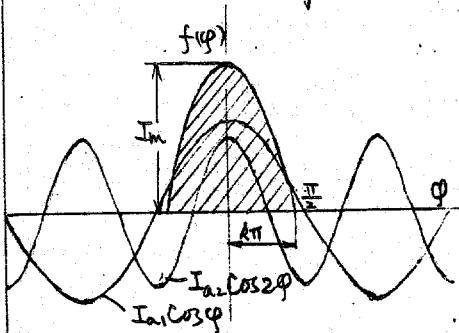


Fig 4 A cosine plate pulse current Fourier analysis Waveform.

Using Fourier analysis, a plate current pulse $f(\phi)$ can be represented as a linear combination of all harmonic Waveform. Fig 4 shows the fundamental and second harmonic wave and their phase relation.

$$f(\phi) = \begin{cases} \cos \phi & -k\pi \leq \phi \leq k\pi \\ 0 & \phi < -k\pi, \phi \geq k\pi \end{cases}$$

$$f(\phi) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos n\phi$$

$$a_0 = \frac{2}{\pi} \int_0^\pi f(\phi) d\phi = \frac{2}{\pi} \sin k\pi$$

$$a_n = \frac{2}{\pi} \int_0^\pi f(\phi) \cos n\phi d\phi = \frac{2}{\pi} \left[\frac{\sin(1+n)k\pi}{2(1+n)} + \frac{\sin(1-n)k\pi}{2(1-n)} \right]$$

If the plate circuit really resonates at the harmonic components the output voltage will have the same phase as output current. The synthetic waveform shown in Fig 5. The desired waveform could not be got because of relative phase unsuitable.

Same phase as output current, The synthetic waveform shown in Fig 5. The desired waveform could not be got because of relative phase unsuitable.

To generate suitable waveform. A phase shift of one of component has to be made by changing resonant frequency. It means that changes the output circuit impedance at operating frequency to get a phase shift. Since second harmonic component needed is small. Changing the resonant frequency has a small influence.

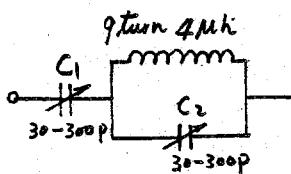


Fig 6.

A simple circuit shown in Fig 6 has been put across the gap of P.P.A Cavity to get non-sinusoidal voltage waveform. The ferrite permeability μ changes with magnetic field flux intensity B , consequently with plate RF Voltage. For different output power both C₁ and C₂ have different values to get resonant frequency. The plate output equivalent circuit shown in Fig 7. For convenience first

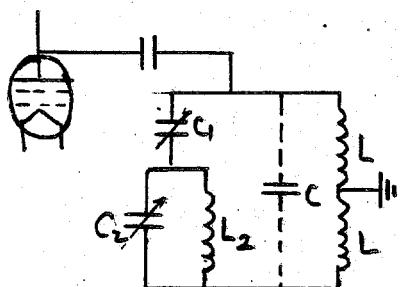


Fig 7 plate output equivalent circuit. C gap capacitor L ferrite inductor

Using impedance meter set the circuit resonant frequencies nearly harmonic frequencies ("cold condition") then exciting cavity at requirement

output power condition ("hot condition") tuning C₁ and C₂ again to get suitable waveform. But the suitable

phase relation and the ratio of amplitude are not easy to get at the same time, so if only one gap used, it is difficult to get desired waveform.

A P.P.A cavity has two gaps, only one gap adds second harmonic component, then two gap - voltages superimpose to get the required voltage. There are two ^{options} selections to superimpose two sides. One is that both sides resonate at fundamental frequency, at the same time, one of them has complex impedance at second harmonic frequency. In this condition the fundamental wave phase of two sides are the same; the

second harmonic has a phase shift. The amplitude ratio is set by adjusting screen DC bias Voltage. Sometime for some reason, such as two sides fixative phase shift different, fundamental wave impedance not really resistor, the fundamental phase between two sides is not zero. It can be compensated by adjusting exciting Voltage phases. This condition shown in Fig 8.

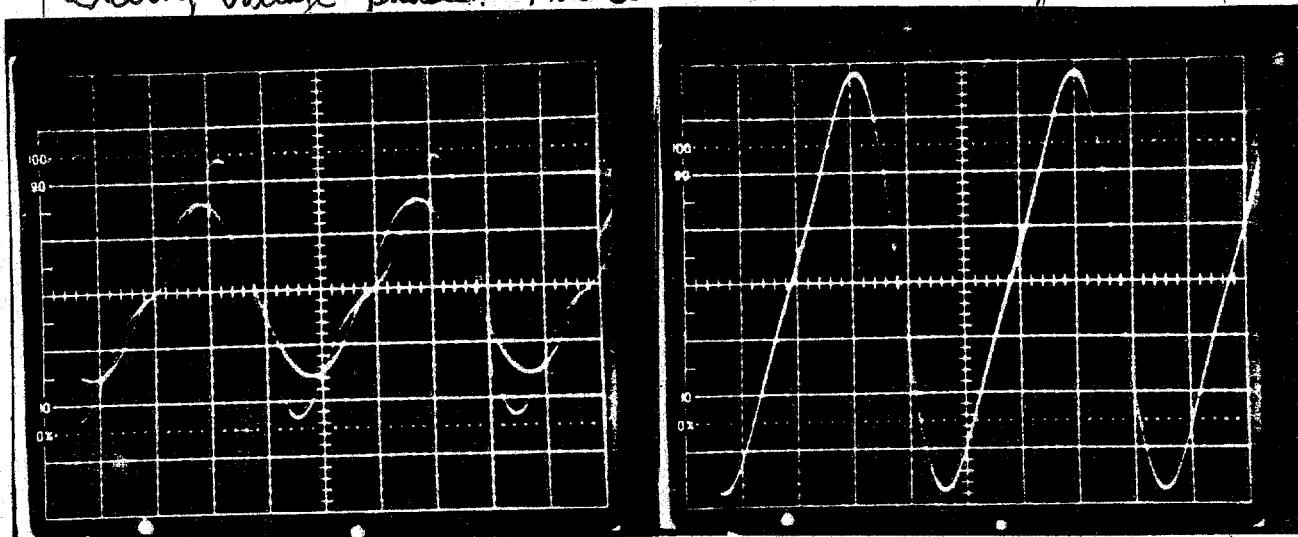


Fig 8. two sided resonance a) two gap waveform b) added waveform

The other is that one side resonates at fundamental frequency, other side does not really resonate at any harmonic frequency. The desirable superimposed waveform has been got by tuning C_1 and C_2 . Never mind what one side Voltage Waveform is, as long as the added Waveform is desired. Waveform as shown in Fig 9.

At "hot condition", As second harmonic added in the same gap. the resonant frequency can not be measured, so it is not easy to say what Condition it is operating in, only from waveform got some information. Normally in between two. Here is an example in Fig 10. The impedance data was measured at "cold condition" by Using impedance meter. The operating frequency

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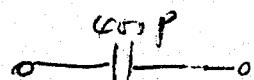
9 twins 4MHz



4R

53-7-13

8



Using impedance meter measured resonant frequencies at gaps

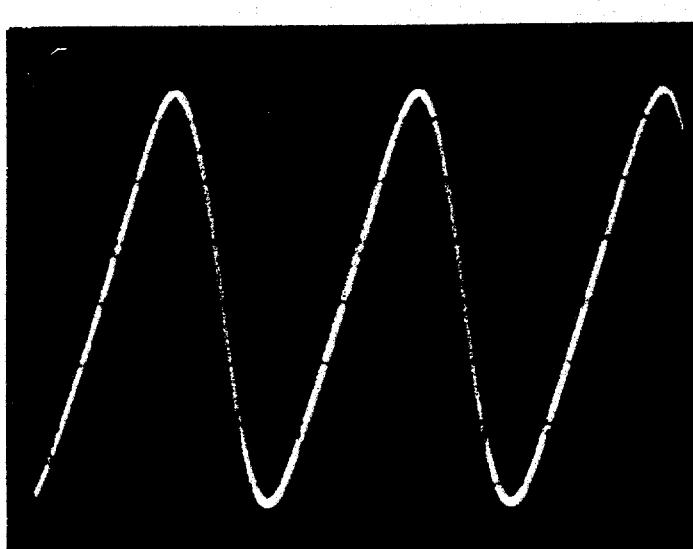
f	θ	Q	f	θ	Q
2.692	95	90	2796	88°	90
2701	2.6°	70	2914	2.8°	70
2731	6.7°	45	2943	4.8°	45
$\alpha = 138$	2764	5.65°	0	$Q = 72.3$	2964
	2774	4.3°	-45		2984
	2781	2.5°	-70		3007
	28.0	5.2°	-90		3111°
	3390	1.5°	0		
	4788	69.0°	+90		
	4973	1.76°	+70		
$Q = 51.6$	5059	3.1°	+45		
	5111	4.4°	0		
	5158	3.4°	-45		
	5212	2.05°	-70		
	5492	59.0°	-90		

$$V_p = 8 \text{ kV}$$

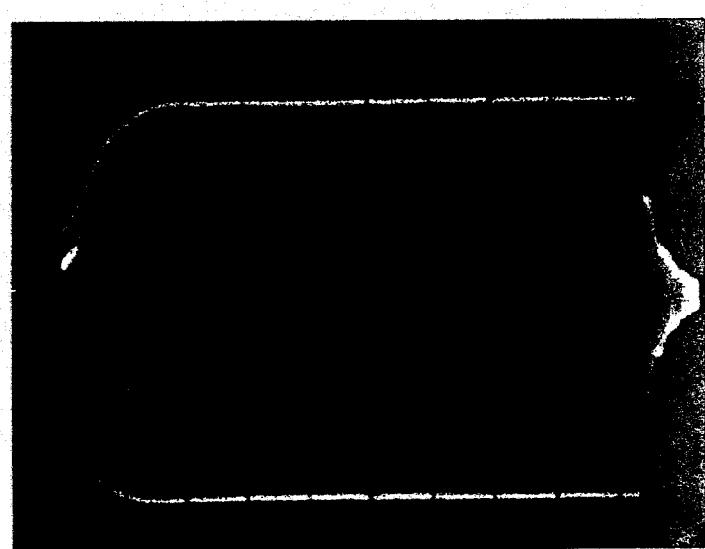
$$V_s = 400 \text{ V}$$

$$V_g = -400 \text{ V}$$

Driving RF Voltage $\approx 500 \text{ V}$ peak
The phase between two side is about 180°



$1 \times 3600 \text{ V/DIV}$
 0.1 MS/DIV
 $f = 2529.4 \text{ MHz}$
 $\theta = 0.64\pi$



$1 \times 3600 \text{ V/DIV}$
 20 MS/DIV

The Period is 50 ns

Fig 10 Two sides added non-sinusoidal waveform example 4[#] P.PA Cavity

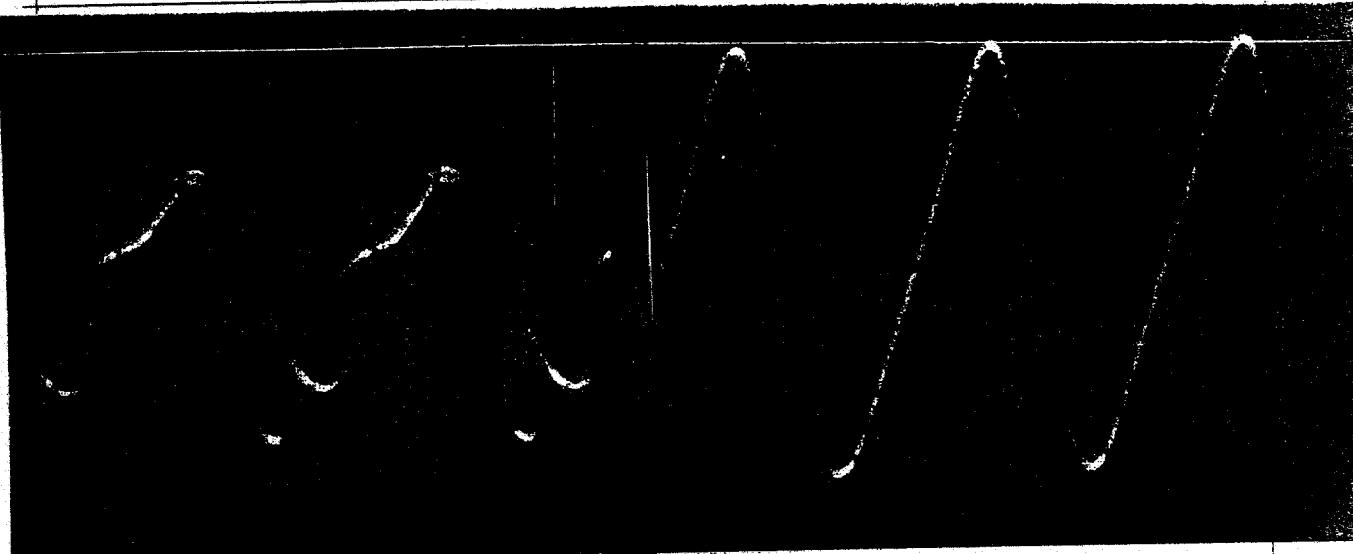


Fig 9 One side resonance at fundamental frequency.
 a) two gap waveform b) added waveform.

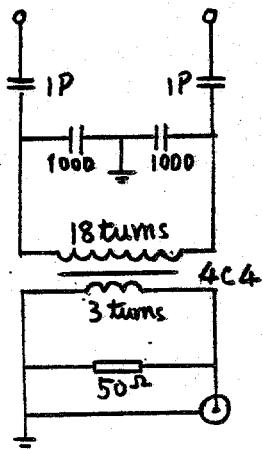


Fig 11 The monitor

is 2.5294 MHz. output RF Voltage is about 12.5 kV peak. In fact the C_1 mainly influences the fundamental resonant frequency, the C_2 mainly influences the second harmonic resonant frequency.

Since all the voltage waveform and amplitude are got from the monitor the phase shift and amplitude ratio of monitor must be the same in two sides. The monitor shown in Fig 11 has been used, the ferrite is ferrxcube 4C4.

The conclusion is that for single working frequency using this method to add higher harmonic components can get better linear waveform, high efficiency and less hardware.

The adjustment steps as follow.

- ① Using impedance meter set the output circuit resonates nearby harmonic frequencies.
- ② tuning C_1 to make Voltage amplitude to reach maximum. it means the circuit resonates nearby fundamental frequency.
- ③ tuning C_2 to make two harmonic components have suitable phase relation. at this condition the waveform will be fold symmetry.
- ④ estimating the amplitude rate of two components. If it is not suitable. tune C_1 and C_2 to change the rate but to try keeping suitable phase relation.

After practicing a few times one would know how could do it easier and faster. Maybe steps ②-④ is not necessary just watching and tuning.

- ⑤ Two sides added trimming C_1 and C_2 to get desirable waveform and amplitude.